Left ventricular thrombus after acute ST-segment elevation myocardial infarction Multi-parametric cardiac magnetic resonance imaging with long-term outcomes

Shi, Ruo yang; Chen, Bing hua; Wu, Chong wen; Wesemann, Luke; Hu, Jiani; Xu, Jian rong; Zhou, Yan; Tao, Qian; Wu, Lian ming

DOI
10.1007/s10554-022-02598-9

Publication date
2022

Document Version
Final published version

Published in
International Journal of Cardiovascular Imaging

The International Journal of Cardiovascular Imaging (2022) 38:2373–2384
https://doi.org/10.1007/s10554-022-02598-9

ORIGINAL PAPER

Left ventricular thrombus after acute ST-segment elevation myocardial infarction: multi-parametric cardiac magnetic resonance imaging with long-term outcomes

Ruo-yang Shi[1] · Bing-hua Chen[1] · Chong-wen Wu[1] · Luke Wesemann[2] · Jiani Hu[2] · Jian-rong Xu[1] · Yan Zhou[1] · Qian Tao[3,4] · Lian-ming Wu[1]

Received: 15 December 2021 / Accepted: 11 March 2022 / Published online: 27 March 2022

Abstract

Left ventricular thrombus (LVT) after acute ST-segment elevation myocardial infarction (STEMI) are generally associated with poorer outcomes for patients at long-term follow-up. We hypothesis that tissue characteristics and strain parameters by cardiac magnetic resonance (CMR) imaging may indicate the interactions of LVT with ventricular myocardium remodeling at both acute stage and chronic stages in STEMI patients. This retrospective study included 111 consecutive STEMI patients (38 with LVT and 73 without LVT). All patients underwent CMR during acute stage (within 7 days) and chronic stage (after at least 2 months) periods after percutaneous coronary intervention (PCI). Left ventricular native T1, extracellular volume (ECV), radial, circumferential, and longitudinal strain were analyzed in both phases. Major adverse cardiac events (MACE, including cardiovascular death, myocardial reinfarction, and hospitalization for heart failure), thromboembolic and bleeding events, were the clinical endpoints of the study. During the acute stage, left ventricular ejection fraction (LVEF) (OR 0.77, P value = 0.01) and longitudinal strain (OR 1.90, P value < 0.001) were correlated with LVT formation. Strain parameters were reduced, while the native T1 and ECV values of both the infarcted area and remote myocardium were elevated in LVT patients. During the chronic stage, LVT resolved in 29 of 38 patients (76%). LVT remaining patients had lower LVEF, a larger LV, and higher ECV in the acute stage than those of the LVT-resolved patients. In the long-term follow up of 678 days, LVT (HR 2.45, P value = 0.02), aneurysm (HR 1.81, P value = 0.04), and native T1 (HR 2.44, P value = 0.01) were identified as three independent predictors of MACE, the incidence of thromboembolic events and bleeding events by a multivariable stepwise Cox proportional hazards regression. STEMI patients developing LVT had worse LV function, myocardial infarction extent, strain, and higher T1 and ECV values than STEMI patients without LVT. The LVT-remaining patients in the chronic stage had poorer functional and mapping parameters beginning in the first week. During the acute stage, LVEF and global longitudinal strain were independent correlated with LVT formation. During the long-term follow up, LVT, aneurysm and elevated myocardial T1 were associated with adverse outcomes in acute STEMI patients.

Keywords Left ventricular thrombus · T1 map · Extracellular volume · Strain analysis

✉ Yan Zhou
clare1475@outlook.com

✉ Qian Tao
q.tao@tudelft.nl

✉ Lian-ming Wu
wlmssmu@126.com

[1] Department of Radiology, Ren Ji Hospital, School of Medicine, Shanghai Jiao Tong University, No. 160, Pujian Road, Shanghai, China

[2] Department of Radiology, Wayne State University, Detroit, MI, USA

[3] Department of Imaging Physics, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands

[4] Division of Imaging Processing, Department of Radiology, Leiden University Medical Center, Albinusdreef 2, 2333 ZA Leiden, The Netherlands

Abbreviations

CMR	Cardiac magnetic resonance
MACE	Major adverse cardiac events
LVT	Left ventricular thrombus
LAD	Left anterior descending
LGE	Late gadolinium enhancement
LVEF	Left ventricular ejection fraction
LVEDVi	Left ventricular end-diastolic volume index
LVESVi	Left ventricular end-systolic volume index
LVMi	Left ventricular mass index
GRS	Global radial strain
GLS	Global longitudinal strain
GCS	Global circumferential strain
ECV	Extracellar volume

Introduction

The incidence of left ventricular thrombus (LVT) formation has declined since the widespread use of percutaneous coronary intervention (PCI), but may still occur in 4–25% of patients with acute myocardial infarction (AMI) [1–5]. To date, the mechanisms of LVT formation are not fully understood. Previous research has identified a number of risk factors for LVT, including reduced left ventricular ejection fraction [4, 6], infarct size [7, 8], left anterior descending (LAD) coronary artery obstruction [9], and apical ventricular wall hypokinesis [10, 11].

LVT is an established independent predictor of long-term adverse cardiovascular events. In patients with LVT, the reported risk of death, major adverse cardiovascular events (MACE) [12], and embolic complications [13] were higher than patients without LVT formation. In addition, when antithrombotic therapy includes a vitamin K antagonist and oral anticoagulants (OAC), LVT patients may suffer from major bleeding events, which are highly dangerous.

Cardiac magnetic resonance (CMR), with its excellent resolution and tissue characterization, is a highly sensitive imaging modality to diagnose LVT compared with echocardiography [11, 14, 15]. CMR can visualize the presence of LVT, as well as the location of thrombi with its versatile sequences. On late gadolinium enhancement (LGE) images, LVT can be observed as intra-ventricular hypointensity filling defects, generally adherent to the infarcted area [13]. Currently, CMR studies of LVT mainly focus on blood flow [16] and LV geometrical and functional parameters [10]. With the development of imaging and image analysis techniques, T1 mapping has become a reliable quantitative tool to characterize myocardial tissue, including tissue tracking as a novel tool to characterize myocardial wall motion. However, either tool has not been widely implemented in LVT research, although they have been extensively studied in ischemia and non-ischemia cardiomyopathy cohorts [17–19]. We hypothesize that the myocardial infarction, edema, and interstitial fibrosis, as quantitatively assessed by CMR T1 mapping, may provide invaluable information on the association between myocardial tissue and intracavity LVT. Moreover, we hypothesize that the tissue tracking technique, which allows accurate evaluation of radial, circumferential and longitudinal strain of the LV, may provide valuable insight on LVT development from a mechanical point of view.

Accordingly, the aims of this study are as follows: (1) to determine if quantitative tissue characterization, including native T1, ECV and strain, are associated with LVT formation (acute stage) and resolution (chronic stage) in ST-segment elevation myocardial infarction (STEMI) patients; (2) to uncover the risk factors and long-term outcomes (MACE, thromboembolic and bleeding events) of STEMI patients with and without LVT. By studying the diagnostic and prognostic value of quantitative CMR, we aim to investigate the value of CMR in the management of STEMI patients with LVT.

Methods

This retrospective study was approved by the Internal Review Board at our institution. All patients provided written informed consent.

Patient selection

In our institution, STEMI patients took the first CMR examination usually within 1 week after PCI in hospital. During the monthly outpatient follow-up, CMR was recommended by cardiologists to patients as follow-up study. In this study, a total of 156 consecutive patients diagnosed with STEMI treated with PCI between August 2016 and December 2019, and underwent CMR twice in our institute (within 7 days and at least 60 days after PCI), were included. Patients with a history of non-ischemic cardiomyopathy (n = 16) and previous myocardial infarction (MI) (n = 25) were excluded from this study. Patients with poor image quality were also excluded (n = 4).

CMR protocol and image analysis

All CMR examinations were performed with a 3.0 Tesla scanner (Ingenia, Philips Healthcare, Best, The Netherlands) with a dS Torso coil anterior to the chest. The imaging protocol included the acquisition of cine (short-axis 8–12 slices cover LV, 2-, 3-, and 4-chamber orientation), T2-weighted short tau inversion recovery (T2-STIR) (short-axis 8–12 slices cover LV), late gadolinium enhancement (LGE) (short-axis 8–12 slices cover LV), native and post-contrast

T1 mapping (short- axis 3 slices cover basal, mid-ventricular and apex level of LV). Long-axis images covering the lesion would be additionally acquired during the scan for double check.

The parameters of performed sequences were as follows: (1) cine: balanced steady-state free precession (b-SSFP) sequence, repetition time (TR) = 2.8 ms, echo time (TE) = 1.4 ms, slice thickness = 7 mm, slice gap = 3 mm, field of view (FOV) = 300 mm × 300 mm, acquired matrix = 0.875 mm × 0.875 mm; (2) T2-STIR: TR = 1714 ms, TE = 75 ms, slice thickness = 7 mm, slice gap = 3 mm, FOV = 300 mm × 300 mm, acquired matrix = 0.89 mm × 0.89 mm; (3) LGE: phase-sensitive inversion recovery (PSIR) sequence 10–15 min after a bolus contrast injection, TR = 6.1 ms, TE = 3 ms, FOV = 300 mm × 300 mm, acquired matrix = 0.89 mm × 0.89 mm, slice thickness = 7 mm, slice gap = 3 mm; (4) native and post contrast T1 mapping: steady-state free-precession single-breath-hold modified look-locker inversion recovery (MOLLI) sequence, initial inversion time (TI) = 100 ms, TI increment = 80 ms, TR = 2.3 ms, TE = 1 ms, FOV = 300 mm × 300 mm, acquired matrix = 1.3 mm × 1.3 mm. The injection plan was 0.15 mmol/kg of gadolinium-DTPA (Magnevist Bayer Healthcare, Berlin, Germany) with 15 ml saline flushing.

All image analysis tasks were performed with cvi42 (version 5.11.4, Circle Cardiovascular Imaging Inc. Calgary, Canada): (1) Strain was analyzed by short-axis stack and 3 long axis cine images in the Tissue Tracking module. LV endo and epicardial borders were automatically traced at end-diastolic phase and manually adjusted to ensure accurate border tracking. Global radial strain (GRS) and global circumferential strain (GCS) were calculated from the short-axis cine, and global longitudinal strain (GLS) was calculated from 2-, 3- and 4-chamber orientation slices. (2) Myocardial edema and infarct size, microvascular obstruction (MVO) and intramyocardial hemorrhage (IMH) presence and extent were analyzed by the Tissue Characterization module. Infarcted area was identified with full-width at half-maximum (FWHM) method in LGE images. (3) Native T1 map and ECV map were generated by the T1 mapping module with native and post contrast T1 sequencing. Besides the values of infarcted and remote area were calculated from the manually delineated region of interest (ROI).

Clinical outcomes assessment

Clinical outcomes were extracted from electronic medical records, and investigators were blinded to the CMR outcome. The primary clinical endpoint of this study was major adverse cardiovascular event (MACE), defined as a composite of cardiovascular death, myocardial reinfarction, hospitalization for heart failure, and the incidence of thromboembolic events and bleeding events (defined by BARC criteria [20]). Each patient contributed only once to the combined end point in the case of multiple events.

Statistical analyses

Continuous variables were expressed as means ± SDs. Data not normally distributed were reported in medians and inter-quartile ranges (IQRs). Comparison between LVT and non-LVT groups, LVT-resolved and LVT-remaining groups were performed by non-paired t-test and the nonparametric Mann–Whitney U test. Group percentages were compared by x^2 test or the Fisher exact test where appropriate. Univariable and multivariable stepwise logistic regression were performed to predict the LVT formation. Odds ratios with the respective 95% confidence intervals (CIs) were computed. Cumulative incidence was obtained by Kaplan–Meier analysis and compared by log-rank test. Univariable and multivariable stepwise Cox proportional hazards regression model was used to identify independent predictors. Hazard ratio as 95% CIs were calculated. All statistical analyses were two tailed, with a P value of < 0.05 denoting statistical significance. R version 4.0.3 with RStudio version 1.3.959 and SPSS version 22.0 (IBM, Armonk, New York) was used for all the statistical analyses.

Results

Characteristics of patients and LVT

A total of 111 patients (38 with LVT, 73 with non-LVT) were included in this study. Clinical characteristics are summarized in Table 1. The mean age, sex, body surface area (BSA) and prevalence of hypertension, dyslipidemia, diabetes mellitus were not significantly different between the 2 groups. But the prevalence of LAD as the cult vessel in LVT patients was significantly higher than non-LVT patients (36/38 vs 53/73, P = 0.02). The inclusion flowchart was showed in Fig. 1.

Of all the 38 LVT patients, 25 had a protuberant thrombus. Most LVTs (35/38) were adjacent to the infarct and at the apical level. After detection of LVT, 27 patients started or continued on aspirin, 37 patients started or continued on an anticoagulant, and 16 patients were on an anticoagulant with an antiplatelet. The one patient not treated with anticoagulants had a high bleeding risk and was treated with aspirin only. During a median follow-up of 678 days (interquartile range 338–1016 days), 29 patients had a completely resolved LVT after antithrombotic therapy.

Table 1 Baseline characteristics of patients with LVT (n = 38) and non-LVT patients (n = 73)

Characteristics	LVT (n = 38)	Non-LVT (n = 73)	*P* value
Age, y ± SD	60.4 ± 10.3	60.7 ± 11.5	0.61
Men, %	36	63	0.54
Body surface area, m^2 ± SD	1.8 ± 0.2	1.8 ± 0.2	0.58
Hypertension, %	23 (60.0)	46 (63.0)	0.69
Dyslipidemia, %	21 (53.8)	47 (64.4)	0.31
Diabetes mellitus, %	5 (12.8)	11 (15.1)	0.99
Tobacco use, %	20 (51.3)	39 (53.4)	0.85
Infarcted coronary artery			
LAD	36	53	0.02
LCX	5	6	0.51
RCA	4	22	0.06
LV aneurysm	16/38	18/73	0.08

LVT left ventricular thrombus; *LV* left ventricle; *LAD* left anterior descending; *LCX* left circumflex branch; *RCA* right coronary artery

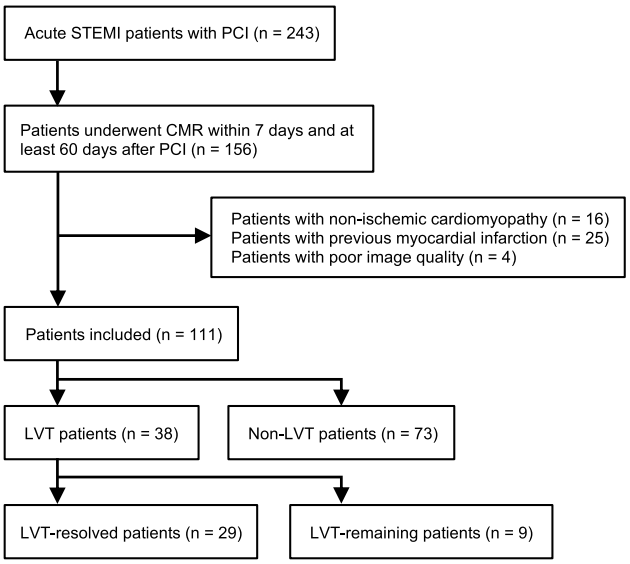

Fig. 1 Study flow chart

LVT versus non-LVT patients

The quantitative CMR parameters were summarized in Table 2. During the acute stage, the left ventricular ejection fraction (LVEF) (39.09 ± 10.40 ml vs 53.37 ± 10.97 ml, P < 0.001), indexed left ventricular end diastolic (LVEDVi) (98.04 ± 26.74 ml vs 79.40 ± 20.60 ml, P = 0.01) and left ventricular systolic volume (LVESVi) (61.47 ± 24.99 ml vs 38.36 ± 18.34 ml, P < 0.001), infarcted size (34.83 ± 13.09% vs 25.80 ± 15.66%, P = 0.02) were all significantly different in LVT and non-LVT groups. The GRS (13.72 ± 4.87% vs 21.84 ± 7.69%, P < 0.001), GLS (− 7.63 ± 1.93% vs − 11.23 ± 2.96%, P < 0.001), GCS (− 9.15 ± 2.66% vs − 13.46 ± 3.67%, P < 0.001) of LVT patients was significantly lower than those of the non-LVT group. Native T1 and ECV of the whole myocardium (Native T1: 1438.70 ± 99.48 ms vs 1365.03 ± 76.01 ms, P = 0.01; ECV: 41.76 ± 6.16 vs 35.94 ± 4.54, P < 0.001) and infarcted zone (native T1: 1632.16 ± 132.49 vs 1548.82 ± 173.08, P = 0.04; ECV: 65.46 ± 12.79 vs 54.47 ± 11.31, P < 0.001) were significantly elevated in the LVT group.

During the chronic stage, LVT and non-LVT patients both showed a similar tendency of EF and LVESVi not changing significantly compared with the acute stage. LVEDVi values of both groups slightly increased and LGE extent reduced during the chronic stage. The GRS, GCS, GLS of non-LVT group improved during the chronic stage. Conversely in the LVT group, only GLS was significantly changed during the chronic stage (− 7.63 ± 1.93 vs − 9.29 ± 2.74, P = 0.01). Native T1 and ECV of the whole myocardium, infarcted zone and remote zone in both groups had all reduced during the chronic stage. Remarkably, the remote zone of ECV in the LVT group did not show statistically significant changes between the acute stage and chronic stages. The change rate [(chronic stage CMR parameter – acute stage CMR parameter)/acute stage CMR parameter] of all parameters from acute stage to chronic stages only showed significant differences in the infarcted zone ECV in the LVT group.

Univariate and multivariate analyses of clinical and CMR variables for thrombus formation in STEMI patients are summarized in Table 3. In the multivariable analysis, only LVEF (Odd ratio: 0.77, 95% CI 0.64, 0.94, P = 0.01) and GLS (Odd ratio: 1.90, 95% CI 1.27, 2.86, P < 0.001) were identified as the independent markers for thrombus formation.

LVT-resolved versus LVT-remaining patients

Of the 38 LVT patients, the LVT in 29 completely resolved during the chronic stage, while it was not resolved in 9 patients. The CMR parameters are summarized in Table 4. The LVT-remaining group showed significantly lower EF, lager LVEDVi, and LVESVi in the acute stage than the LVT-resolved group. The GRS, GCS and ECV were significantly different between groups. During the chronic stage, the LV conventional parameters (including LVEF, LVEDVi, LVESVi, LVMi) of LVT-remaining patients did not exhibit significant recovery. Even the infarct size did not significantly reduce during the chronic stage. In addition, the GRS and GCS stayed low during the chronic stage. The native T1 and ECV of whole myocardium significantly reduced in the LVT-remaining group in the chronic stage study (native T1: 1464.31 ± 140.56 ms vs 1358.18 ± 82.73 ms, P = 0.01; ECV: 45.08 ± 4.99% vs 39.28 ± 5.25%, P = 0.011) but were

Table 2 Acute and Chronic stage CMR characteristics comparison of LVT (n = 38) and Non-LVT (n = 73) patients

	LVT (n = 38)			Non-LVT (n = 73)			Acute stage comparison P value	Change rate comparison P value
	Acute stage study	Chronic stage study	Paired comparison P value	Acute stage study	Chronic stage study	Paired comparison P value		
LVEF, % ± SD	39.09 ± 10.40	38.68 ± 12.73	0.86	53.37 ± 10.97	53.63 ± 11.88	0.78	< 0.001	0.97
LVEDVi, ml/m^2	98.04 ± 26.74	105.62 ± 26.86	0.04	79.40 ± 20.60	81.47 ± 18.89	0.24	0.01	0.31
LVESVi, ml/m^2	61.47 ± 24.99	66.93 ± 29.10	0.24	38.36 ± 18.34	39.14 ± 18.32	0.53	< 0.001	0.42
LVMi, g/m^2	62.95 ± 10.40	58.63 ± 11.43	0.09	64.31 ± 11.44	60.70 ± 10.86	< 0.001	0.64	0.76
Infarct size, % of LV	34.83 ± 13.09	27.67 ± 10.42	0.01	25.80 ± 15.66	18.41 ± 13.25	< 0.001	0.02	0.98
GRS, %	13.72 ± 4.87	15.11 ± 5.19	0.19	21.84 ± 7.69	23.68 ± 7.18	0.01	< 0.001	0.79
GLS, %	− 7.63 ± 1.93	− 9.29 ± 2.74	0.01	− 11.23 ± 2.96	− 12.11 ± 3.71	0.04	< 0.001	0.21
GCS, %	− 9.15 ± 2.66	− 10.28 ± 2.93	0.07	− 13.46 ± 3.67	− 14.75 ± 3.39	< 0.001	< 0.001	0.65
T1 value, ms	1438.70 ± 99.48	1357.83 ± 62.99	< 0.001	1365.03 ± 76.01	1313.01 ± 58.09	< 0.001	0.01	0.16
T1 value of infarct zone, ms	1632.16 ± 132.49	1505.15 ± 116.36	< 0.001	1548.82 ± 173.08	1466.85 ± 139.02	< 0.001	0.04	0.20
T1 value of remote zone, ms	1269.04 ± 54.36	1234.17 ± 72.38	0.01	1242.30 ± 60.68	1211.13 ± 61.63	< 0.001	0.09	0.74
ECV, %	41.76 ± 6.16	38.04 ± 5.39	< 0.001	35.94 ± 4.54	33.26 ± 4.51	< 0.001	< 0.001	0.46
ECV of infarct zone, %	65.46 ± 12.79	52.65 ± 10.43	< 0.001	54.47 ± 11.31	47.04 ± 8.74	< 0.001	< 0.001	0.02
ECV of remote zone, %	27.12 ± 3.88	26.32 ± 2.25	0.29	25.89 ± 2.82	24.14 ± 2.54	< 0.001	0.23	0.14

LV left ventricle; *LVEF* left ventricular ejection fraction; *LVEDVi* left ventricular end-diastolic volume index; *LVESVi* left ventricular end-systolic volume index; *LVMi* left ventricular mass index; *GRS* global radial strain; *GLS* global longitudinal strain; *GCS* global circumferential strain; *ECV* extracellular volume; Change rate = (chronic stage CMR parameter – acute stage CMR parameter)/acute stage CMR parameter

still slightly higher than the LVT-resolved group (native T1: 1358.18 ± 82.73 vs 1334.87 ± 67.32, P = 0.48; ECV: 39.28 ± 5.25 vs 34.77 ± 4.50, P = 0.049).The acute stage and chronic stage CMR images of examples in LVT-remaining, LVT-resolved and Non-LVT groups were summarized in Figs. 2 and 3.

Follow-up study of LVT and non-LVT patients

Clinical follow-up was completed for all patients. The composite end point as defined previously occurred significantly more often (P = 0.01) in the LVT group (12/38 cases) than in the non-LVT group (9/73 cases) during at follow up. On Kaplan–Meier analysis comparing LVT and non-LVT patients, the cumulative incidence of the clinical endpoint was significantly higher in LVT patients than in non-LVT patients (P = 0.01; Fig. 4). Baseline and CMR parameters were selected in Cox univariable analyses, and variables statistically associated with the end point at a P value < 0.05 were assessed in multivariable analyses (Table 5). Finally, LVT (Harzard ratio: 2.45, 95% CI 1.39, 4.65, P = 0.02), LV aneurysm (Harzard ratio: 1.81, 95% CI 0.56, 5.82, P = 0.04), and Native T1 value (Harzard ratio: 2.44, 95% CI 1.22, 4.88, P = 0.01) were identified as the independent predictors of the endpoint.

Discussion

We present a CMR study for a group of STEMI patients with and without LVT. The patients were followed for at least 2 months primarily looking for long-term outcomes in terms

Table 3 Logistic regression analysis of variables which influence presence of LVT

	Univariable		Multivariable	
	Odd ratio (95% CI)	*P* value	Odd Ratio (95% CI)	*P* value
Gender	1.81 (0.19, 17.58)	0.37		
Age (y)	0.97 (0.91, 1.04)	0.84		
LVEDVi	1.16 (1.02, 1.32)	< 0.001	1.16 (1.03, 1.30)	0.08
LVESVi	0.89 (0.74, 0.98)	0.007	0.82 (0.69, 0.96)	0.06
LVEF	0.86 (0.67, 0.99)	0.004	0.77 (0.64, 0.94)	0.01
LVMi	0.86 (0.78, 0.95)	0.91		
LV aneurysm	0.30 (0.06, 1.57)	0.06		
Infarct size	0.93 (0.83, 0.98)	0.006	0.93 (0.86, 1.02)	0.11
MVO/IMH size	1.44 (0.31, 6.80)	0.33		
GRS	1.52 (1.05, 2.70)	< 0.001	1.25 (0.77, 2.03)	0.36
GLS	2.80 (1.60, 4.91)	< 0.001	1.90 (1.27, 2.86)	< 0.001
GCS	1.59 (1.01, 4.94)	< 0.001	1.17 (0.45, 3.08)	0.75
T1 value	1.05 (0.17, 6.52)	0.03	0.91 (0.35, 2.41)	0.85
T1 value of infarct zone	1.08 (1.01, 2.1)	0.01	1.10 (0.67, 1.8)	0.70
T1 value of remote zone	0.78 (0.17, 3.64)	0.09		
ECV	1.05 (1.01, 1.4)	0.007	1.08 (0.88, 1.32)	0.48
ECV of infarct zone	0.98 (0.91, 0.99)	0.047	0.99 (0.92, 1.05)	0.64
ECV of remote zone	0.94 (0.80, 1.11)	0.11		

LV left ventricle; *LVEF* left ventricular ejection fraction; *LVEDVi* left ventricular end-diastolic volume index; *LVESVi* left ventricular end-systolic volume index; *LVMi* left ventricular mass index; *GRS* global radial strain; *GLS* global longitudinal strain; *GCS* global circumferential strain; *ECV* extracellular volume

of MACE. The major findings were as follows: First, we demonstrated that in STEMI patients with LVT formation, the quantitative LV functional and strain parameters, as well as the native T1 and ECV parameters, were poorer compared those STEMI patients without LVT formation. Second, those patients who had their LVT resolved in the chronic stage exhibited better functional and mapping parameters beginning in the acute stage compared with those LVT-remaining patients. Third, in a long run, we identified thrombi, aneurysm, and global native T1 values as independent risk factors for the long-term outcome. This study demonstrated the capability of CMR tissue and strain mapping techniques in diagnosis and prognosis of STEMI patients.

Previous studies reported an incidence of 4–26% for LVT formation in STEMI patients, and we included 38 (34.2%) STEMI patients with LVT formation in this study. For all patients who underwent CMR during the chronic stage, the LVT patients were more willing to choose CMR as a follow-up examination. In comparison with prior studies, our study included both acute and chronic CMR parameters comprising T1 mapping and strain parameters. With our design and relatively long-term span (median follow-up of 678 days, interquartile range 338–1016 days), LVT formation, myocardium recovery, and long-term outcome were all studied in our cohort.

Up to now, LV dysfunction has been commonly considered as the strongest independent predictor of LVT formation, mainly characterized by LVEF parameters [3, 4, 6]. However, LVEF is relatively insensitive to the regional myocardial tissue and motion remodeling. In contrast, myocardial strain has demonstrated to be a more sensitive marker of myocardial dysfunction on both segmental and global level. In our study, GRS, GCS, and GLS were all reduced in the LVT-formation group, and GLS was identified as an independent predictor of LVT formation. Anterior-apical infarction (LAD coronary artery area) was also identified as a major risk factor related to LVT formation after AMI [4, 21]. In this study, the incidence of LAD area infarction of STEMI with the LVT group was significantly higher than in the non-LVT group (36/38 vs 53/73, P = 0.02). However, the LAD area infarction only showed statistical significance in univariable logistic regression, but not in multivariate analysis. The apex of the left ventricle is largely considered as the region where thrombi more commonly form (84.2%). The area-specific formation was also observed in patients with LVT in Takotsubo syndrome [22, 23]: apical type is a predisposing condition to thrombi formation (91.1–100%), while mid ventricular and basal types are rarely complicated by LVT.

Previous studies reported larger infarcts in STEMI patients with LVT formation [7], conforming to what we observed in this study. However, we observed that infarct size was not the mere factor of LVT formation in our cohort. We have included strain and mapping parameters

Table 4 Acute and chronic stage CMR characteristics comparison of LVT-remaining and LVT resolved patients

	LVT-remaining (n = 9)			LVT-resolved (n = 29)			Acute stage comparison P value	Chronic stage comparison	Change rate comparison P value
	Acute stage study	Chronic stage study	Paired comparison P value	Acute stage study	Chronic stage study	Paired comparison P value			
LVEF, % ± SD	31.51 ± 6.28	30.49 ± 10.90	0.80	50.30 ± 9.68	50.47 ± 10.39	0.91	< 0.001	< 0.001	0.88
LVEDVi, ml/m^2	118.08 ± 23.47	123.33 ± 28.99	0.41	76.62 ± 17.78	83.31 ± 17.67	0.01	0.001	0.01	0.32
LVESVi, ml/m^2	81.18 ± 20.14	86.81 ± 29.73	0.56	39.03 ± 16.15	42.21 ± 15.94	0.08	< 0.001	0.003	0.82
LVMi, g/m^2	65.934 ± 9.86	61.73 ± 14.11	0.31	63.81 ± 10.40	58.33 ± 7.34	0.002	0.61	0.53	0.86
Infarct size, % of LV	36.94 ± 14.75	33.48 ± 8.67	0.36	29.31 ± 15.63	19.49 ± 12.55	< 0.001	0.23	0.002	0.07
GRS, %	10.82 ± 3.64	12.85 ± 4.00	0.30	19.38 ± 6.81	20.30 ± 5.83	0.41	0.00	< 0.001	0.38
GLS, %	− 7.55 ± 2.41	− 9.01 ± 3.51	0.11	− 9.62 ± 2.74	− 10.43 ± 4.22	0.35	0.06	0.35	0.72
GCS, %	− 7.75 ± 2.18	− 9.01 ± 2.50	0.29	− 12.18 ± 3.44	− 13.16 ± 3.01	0.07	< 0.001	0.002	0.49
T1 value, ms	1464.31 ± 140.56	1358.18 ± 82.73	0.01	1368.62 ± 52.53	1334.87 ± 67.32	0.01	0.10	0.48	0.03
T1 value of infarct zone, ms	1640.09 ± 157.03	1525.83 ± 140.02	0.01	1550.53 ± 107.43	1501.57 ± 160.09	0.15	0.16	0.68	0.17
T1 value of remote zone, ms	1283.54 ± 70.09	1222.27 ± 99.87	0.01	1241.30 ± 50.89	1224.77 ± 63.59	0.18	0.15	0.95	0.04
ECV, %	45.08 ± 4.99	39.28 ± 5.25	< 0.001	37.08 ± 4.56	34.77 ± 4.50	< 0.001	0.002	0.049	0.01
ECV of infarct zone, %	70.04 ± 8.80	54.69 ± 8.32	0.001	58.74 ± 12.70	49.52 ± 9.43	< 0.001	0.01	0.16	0.14
ECV of remote zone, %	28.978 ± 4.386	26.719 ± 2.86	0.11	25.18 ± 2.52	25.04 ± 2.34	0.80	0.046	0.16	0.15

LV left ventricle; *LVEF* left ventricular ejection fraction; *LVEDVi* left ventricular end-diastolic volume index; *LVESVi* left ventricular end-systolic volume index; *LVMi* left ventricular mass index; *GRS* global radial strain; *GLS* global longitudinal strain; *GCS* global circumferential strain; *ECV* extracellular volume; Change rate = (chronic stage CMR parameter – acute stage CMR parameter)/acute stage CMR parameter

in our LVT study, which have been widely used to examine ischemia cardiomyopathy. The native T1 map can differentiate acute and chronic MI, while the ECV can further refine the diagnosis with extracellular contrast agents [24]. A multicenter T1 study of chronic MI [25] reported that the T1 value of the infarcted area was 1621 ± 110 ms and remote area was 1225 ± 75 ms. Our study showed a similar tendency of T1 values but slightly lower T1 value in infarcted area (1548.82 ± 173.08 ~ 1632.16 ± 132.49). In the literature, ECV of AMI is associated with adverse left ventricular remodeling [26], and the T1 value of the remote area is also reported to correlate with LV dysfunction and long-term MACE incidence [27]. In our study, nevertheless, remote T1 values did not demonstrate statistical significance in LVT and Non-LVT groups. We demonstrated that both native T1 and ECV values of the global myocardium and the infarcted area were significantly higher in LVT patients. In the LVT subgroup, those LVT-remaining patients had ECV of both global myocardium and infarct zone significantly higher than those of LVT-resolved patients. Native T1 and ECV values of the global myocardium and infarct zone were also associated with LVT formation in univariable Logistic regression. This phenomenon may indicate that LVT formation is associated with more severe myocardial injury. The global myocardial native T1 value is associated with long-term

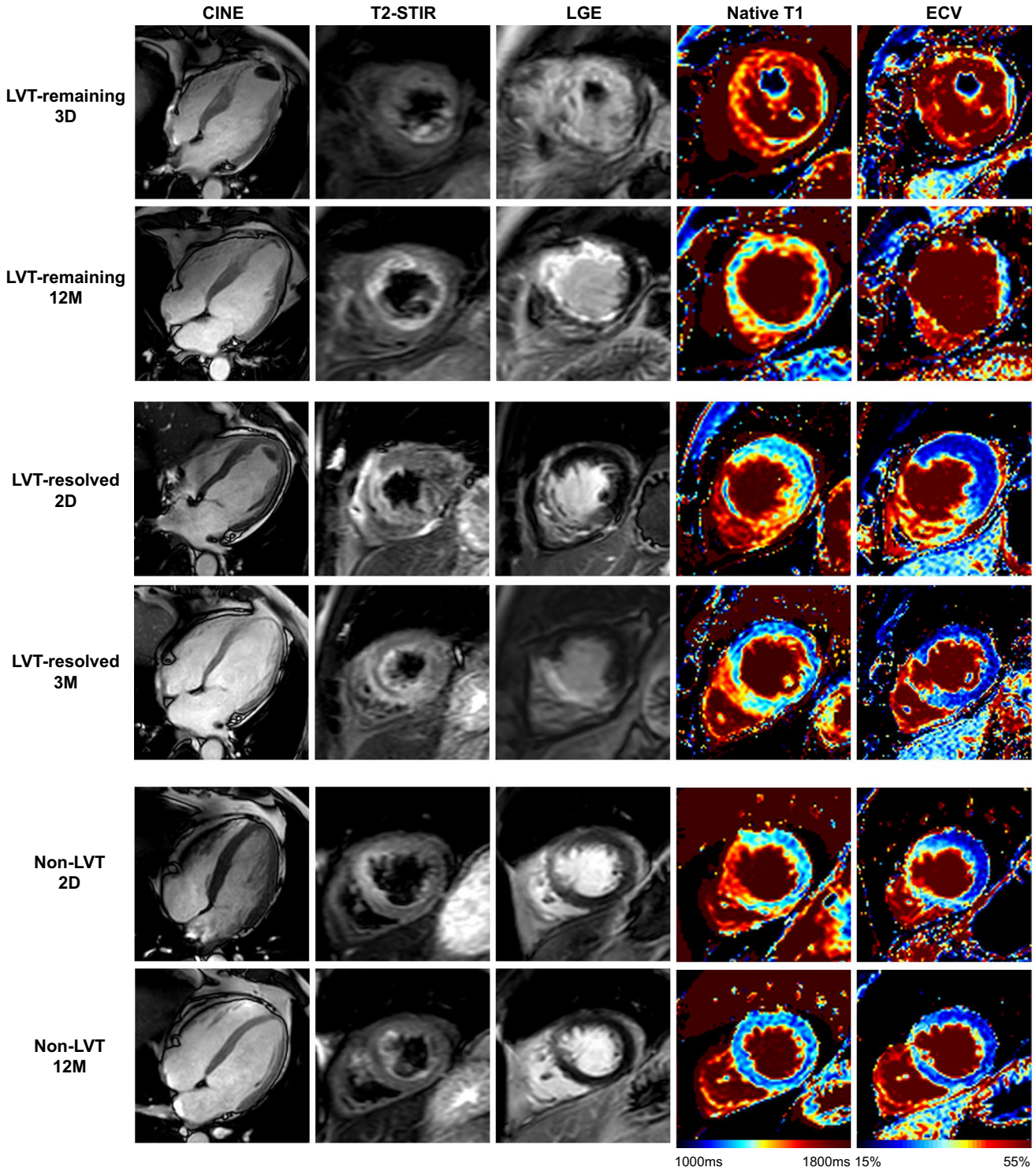

Fig. 2 Examples of LVT-remaining, LVT-resolved and non-LVT patients CMR images in short- and chronic stage

outcomes of STEMI patients (HR 2.44, P value, 0.01). This phenomenon corresponds with previous murine AMI models [28].

In previous studies, LVT regression was achieved in 62.3–86.1% of patients [29, 30]. Patients with persistent LVT reported higher MACE incidence than patients with total LVT regression. In our study, the LVT-remaining patients (9/38, 23.7%) showed severe LV dysfunction and impaired strain than LVT-resolved patients at the first time of CMR test.

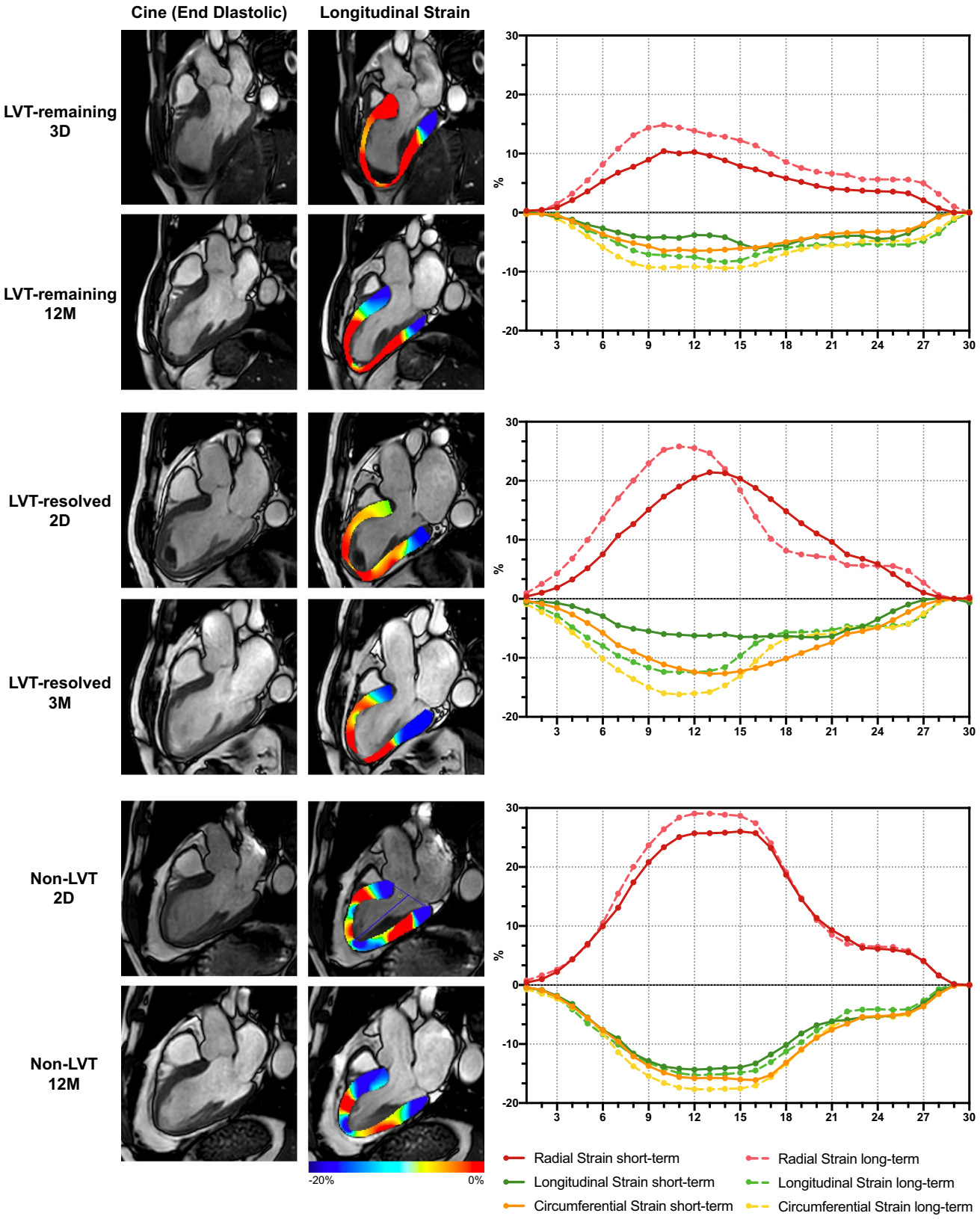

Fig. 3 Strain analysis of LVT-remaining, LVT-resolved and non-LVT patients in short- and chronic stage

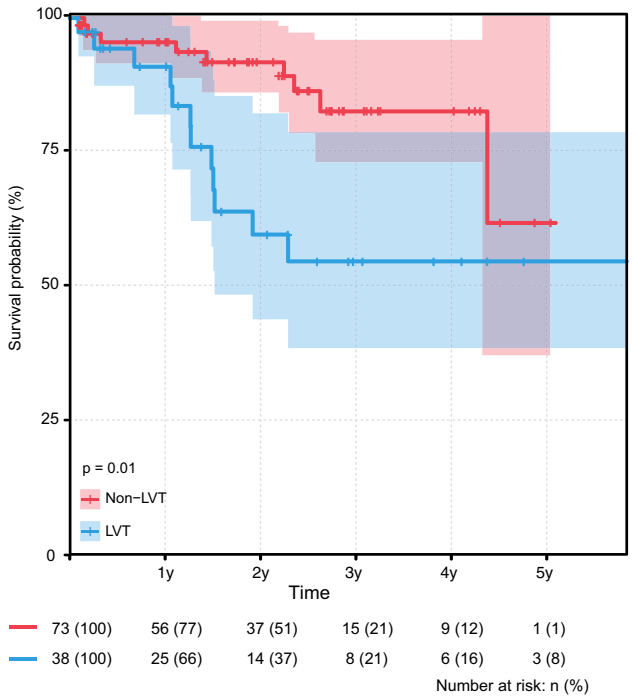

Fig. 4 Kaplan–Meier curves demonstrate the cumulative incidence of LVT and non-LVT patients

Limitations

This was a single-center retrospective study, and possible variations in T1 values related to different MRI machines may exist. The subgroup of LVT-remaining patients was relatively small to study the outcome of the long-term influence of persistent LVT. Another limitation is that the study mainly focused on CMR parameters, while lab tests and blood stasis analysis were available. Finally, given the consideration of reproducibility across software tools, regional strain parameters were not included in this study, while it may be relevant and warrants future study.

Conclusions

We present a quantitative CMR study for a cohort of myocardial infarct patients with and without LVT, followed through acute- and chronic stages, as well as longer-term with respect to composite events. We showed that STEMI patients with poorer functional and mapping parameters during the acute stage are more likely to develop LVT in the acute stage and retain the LVT in the chronic stage. LVEF and GLS were identified as the independent predictors of LVT formation. In a long-term follow up, LVT, aneurysm and global myocardial T1 showed to be associated with adverse events of the patients. Although CMR is currently

Table 5 Associations of the composite end point among LVT (n = 38) and non-LVT patients (n = 73)

	Univariable		Multivariable	
	Hazard ratio (95% CI)	*P* value	Hazard ratio (95% CI)	*P* value
LVT	2.95 (1.24, 7.04)	0.02	2.45 (1.39, 4.65)	0.02
Gender	0.85 (0.25, 2.90)	0.79		
Age (y)	1.03 (0.99, 1.08)	0.16		
LV aneurysm	3.55 (1.49, 8.45)	0.004	1.81 (0.56, 5.82)	0.04
Infarct size, % of LV	1.05 (1.02, 1.08)	0.002	1.00 (0.90, 1.11)	0.99
LVEF	0.92 (0.89, 0.96)	< 0.001	0.87 (0.69, 1.10)	0.25
LVEDVi	1.03 (1.01, 1.04)	< 0.001	1.08 (0.97, 1.20)	0.17
LVESVi	1.03 (1.02, 1.04)	< 0.001	0.92 (0.78, 1.08)	0.29
LVMi	1.04 (1.01, 1.07)	0.01	0.99 (0.94, 1.05)	0.75
GRS	0.87 (0.80, 0.94)	< 0.001	1.06 (0.62, 1.80)	0.83
GLS	1.43 (1.19, 1.73)	< 0.001	1.31 (0.85, 2.02)	0.22
GCS	1.32 (1.14, 1.52)	< 0.001	0.95 (0.37, 2.45)	0.91
T1 value	2.21 (1.46, 3.36)	< 0.001	2.44 (1.22, 4.88)	0.01
T1 value of infarct zone	1.11 (0.87, 1.42)	0.39		
T1 value of remote zone	1.37 (0.67, 2.81)	0.39		
ECV	1.11 (1.00, 1.23)	0.04	0.90 (0.77, 1.05)	0.50
ECV of infarct zone	1.02 (0.98, 1.05)	0.02	1.03 (0.99, 1.08)	0.19
ECV of remote zone	0.95 (0.82, 1.10)	0.50		

LVT left ventricular thrombus; *LV* left ventricle; *LVEF* left ventricular ejection fraction; *LVEDV*, left ventricular end-diastolic volume index; *LVESVi* left ventricular end-systolic volume index; *LVMi* left ventricular mass index; *GRS* global radial strain; *GLS* global longitudinal strain; *GCS* global circumferential strain; *ECV* extracellular volume

not used as the first-level and routine follow-up exam for STEMI patients, it can be considered as a highly sensitive imaging tool for diagnosis, prognosis, and management of LVT.

Acknowledgements Ruo-yang Shi, Bing-hua Chen, and Chong-wen Wu contributed equally to this work. Yan Zhou, Qian Tao and Lianming Wu are the corresponding authors for this article.

Funding This work was supported by the following grants: National Natural Science Foundation of China (Grant Nos. 81873886, 81873887, 8217188); National Natural Science Foundation of China Youth Project (Grant No. 82101981); Shanghai Shenkang Hospital Development Center Clinical Research and Cultivation Project (Grant No. SHDC12018X21); Shanghai Science and technology innovation action plan, technology standard project (Grant No. 19DZ2203800); Shanghai Municipal Education Commission-Gaofeng Clinical Medicine Grant; Shanghai Jiao Tong University school of medicine Double hundred outstanding person project (Grant No. 20191904); Shanghai Sailing Program (Grant No. 22YF1438600); Shanghai Jiao Tong University Medical Engineering cross fund (Grant Nos. YG2022QN016, YG2022QN020, YG2022QN028).

Declarations

Conflict of interest The authors of this manuscript declare no relationships with any companies, whose products or services may be related to the subject matter of the article.

References

1. McCarthy CP, Vaduganathan M, McCarthy KJ, Januzzi JL Jr, Bhatt DL, McEvoy JW (2018) Left ventricular thrombus after acute myocardial infarction: screening, prevention, and treatment. JAMA Cardiol 3(7):642–649
2. Robinson AA, Jain A, Gentry M, McNamara RL (2016) Left ventricular thrombi after STEMI in the primary PCI era: a systematic review and meta-analysis. Int J Cardiol 221:554–559
3. Bulluck H, Chan MHH, Paradies V et al (2018) Incidence and predictors of left ventricular thrombus by cardiovascular magnetic resonance in acute ST-segment elevation myocardial infarction treated by primary percutaneous coronary intervention: a meta-analysis. J Cardiovasc Magn Reson 20(1):72
4. Gianstefani S, Douiri A, Delithanasis I et al (2014) Incidence and predictors of early left ventricular thrombus after ST-elevation myocardial infarction in the contemporary era of primary percutaneous coronary intervention. Am J Cardiol 113(7):1111–1116
5. Meurin P, Brandao Carreira V et al (2015) Incidence, diagnostic methods, and evolution of left ventricular thrombus in patients with anterior myocardial infarction and low left ventricular ejection fraction: a prospective multicenter study. Am Heart J 170(2):256–262
6. Cambronero-Cortinas E, Bonanad C et al (2017) Incidence, outcomes, and predictors of ventricular thrombus after reperfused ST-segment-elevation myocardial infarction by using sequential cardiac MR imaging. Radiology 284(2):372–380
7. Poss J, Desch S, Eitel C, de Waha S, Thiele H, Eitel I (2015) Left ventricular thrombus formation after ST-segment-elevation myocardial infarction: insights from a cardiac magnetic resonance multicenter study. Circ Cardiovasc Imaging 8(10):e003417
8. Hooks M, Okasha O, Velangi PS, Nijjar PS, Farzaneh-Far A, Shenoy C (2020) Left ventricular thrombus on cardiovascular magnetic resonance imaging in non-ischaemic cardiomyopathy. Eur Heart J Cardiovasc Imaging 22(12):1425–1433
9. McCarthy CP, Murphy S, Venkateswaran RV et al (2019) Left ventricular thrombus: contemporary etiologies, treatment strategies, and outcomes. J Am Coll Cardiol 73(15):2007–2009
10. Kaolawanich Y, Boonyasirinant T (2019) Usefulness of apical area index to predict left ventricular thrombus in patients with systolic dysfunction: a novel index from cardiac magnetic resonance. BMC Cardiovasc Disord 19(1):15
11. Weinsaft JW, Kim J, Medicherla CB et al (2016) Echocardiographic algorithm for post-myocardial infarction LV thrombus: a gatekeeper for thrombus evaluation by delayed enhancement CMR. JACC Cardiovasc Imaging 9(5):505–515
12. Zhang Q, Wang CM, Shi ST, Chen H, Zhou YJ (2019) Relationship of left ventricular thrombus formation and adverse outcomes in acute anterior myocardial infarction in patients treated with primary percutaneous coronary intervention. Clin Cardiol 42(1):69–75
13. Velangi PS, Choo C, Chen KA et al (2019) Chronic stage embolic outcomes after detection of left ventricular thrombus by late gadolinium enhancement cardiovascular magnetic resonance imaging: a matched cohort study. Circ Cardiovasc imaging 12(11):e009723
14. Weinsaft JW, Kim HW, Crowley AL et al (2011) LV thrombus detection by routine echocardiography: insights into performance characteristics using delayed enhancement CMR. JACC Cardiovasc Imaging 4(7):702–712
15. Weinsaft JW, Kim HW (2008) Detection of left ventricular thrombus by delayed-enhancement cardiovascular magnetic resonance prevalence and markers in patients with systolic dysfunction. J Am Coll Cardiol 52(2):148–157
16. Garg P, van der Geest RJ, Swoboda PP et al (2019) Left ventricular thrombus formation in myocardial infarction is associated with altered left ventricular blood flow energetics. Eur Heart J Cardiovasc Imaging 20(1):108–117
17. Eitel I, Stiermaier T, Lange T et al (2018) Cardiac magnetic resonance myocardial feature tracking for optimized prediction of cardiovascular events following myocardial infarction. JACC Cardiovasc Imaging 11(10):1433–1444
18. Frojdh F, Fridman Y, Bering P et al (2020) Extracellular volume and global longitudinal strain both associate with outcomes but correlate minimally. JACC Cardiovasc Imaging 13(11):2343–2354
19. Kidambi A, Motwani M, Uddin A et al (2017) Myocardial extracellular volume estimation by CMR predicts functional recovery following acute MI. JACC Cardiovasc Imaging 10(9):989–999
20. Mehran R, Rao SV, Bhatt DL et al (2011) Standardized bleeding definitions for cardiovascular clinical trials: a consensus report from the Bleeding Academic Research Consortium. Circulation 123(23):2736–2747
21. Shacham Y, Leshem-Rubinow E, Ben Assa E et al (2013) Frequency and correlates of early left ventricular thrombus formation following anterior wall acute myocardial infarction treated with primary percutaneous coronary intervention. Am J Cardiol 111(5):667–670
22. Santoro F, Stiermaier T, Tarantino N et al (2017) Left ventricular thrombi in takotsubo syndrome: incidence, predictors, and management: results from the GEIST (German Italian Stress Cardiomyopathy) Registry. J Am Heart Assoc 6(12):e006990
23. Ding KJ, Cammann VL, Szawan KA et al (2020) Intraventricular thrombus formation and embolism in takotsubo syndrome: insights from the International Takotsubo Registry. Arterioscler Thromb Vasc Biol 40(1):279–287
24. Tahir E, Sinn M, Bohnen S et al (2017) Acute versus chronic myocardial infarction: diagnostic accuracy of quantitative native T1 and T2 mapping versus assessment of edema on standard

T2-weighted cardiovascular MR images for differentiation. Radiology 285(1):83–91
25. Wang G, Lee SE, Yang Q et al (2020) Multicenter study on the diagnostic performance of native-T1 cardiac magnetic resonance of chronic myocardial infarctions at 3T. Circ Cardiovasc Imaging 13(6):e009894
26. Yang MX, He Y, Ma M et al (2021) Characterization of infarcted myocardium by T1-mapping and its association with left ventricular remodeling. Eur J Radiol 137:109590
27. Reinstadler SJ, Stiermaier T, Liebetrau J et al (2018) Prognostic significance of remote myocardium alterations assessed by quantitative noncontrast T1 mapping in ST-segment elevation myocardial infarction. JACC Cardiovasc Imaging 11(3):411–419
28. Haberkorn SM, Jacoby C, Ding Z et al (2017) Cardiovascular magnetic resonance relaxometry predicts regional functional outcome after experimental myocardial infarction. Circ Cardiovasc Imaging 10(8):e006025
29. Lattuca B, Bouziri N, Kerneis M et al (2020) Antithrombotic therapy for patients with left ventricular mural thrombus. J Am Coll Cardiol 75(14):1676–1685
30. Jones DA, Wright P, Alizadeh MA et al (2020) The use of novel oral anti-coagulant's (NOAC) compared to vitamin K antagonists (warfarin) in patients with left ventricular thrombus after acute myocardial infarction (AMI). Eur Heart J Cardiovasc Pharmacother 7(5):398–404